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Messinian evaporites in Zakynthos, Greece

N. Kontopoulos [a], A. Zelilidis [a], D.J.W. Piper [b,*], P.J. Mudie [b]

[a] *Department of Geology, University of Patras, Patras, 261 10, Greece*

[b] *Atlantic Geoscience Centre, Geological Survey of Canada (Atlantic), Bedford Institute of Oceanography, P.O. Box 1006, Dartmouth, NS B2Y 4A2, Canada*

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Abstract

Messinian gypsum deposits of central Zakynthos consist of 10–15 m of gypsum turbidites intercalated in a terrigenous turbidite succession. Most of the turbidites are fine grained and thin bedded, perhaps transported by dense briny underflows, but one widespread 2–3 m thick bed of coarse gypsum crystals may have resulted from erosion in shallow water during a sea-level fall. The thickness of overlying terrigenous turbidite and Pliocene shelf sediments shows that the gypsum turbidites accumulated in water depths of less than a few hundred metres. Pollen suggest cooling immediately prior to gypsum deposition and cool dry conditions on land during evaporite formation. Warmer, wetter conditions returned immediately following gypsum deposition. Dinoflagellates provide no evidence for hypersaline marine conditions at the depositional site. In contrast, in eastern Zakynthos, the gypsum unit appears to have accumulated in shallow water and is unconformably overlain by shallow-water Pliocene sediments. © Elsevier Science B.V. All rights reserved.

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1. Introduction

Messinian (late Miocene) evaporites are thick and widespread in the Mediterranean basin. Seismic reflection profiles (Hsü et al., 1977) show that evaporites underlie most of the deep basins of the Mediterranean Sea and in many places the continental margins were eroded and dissected at about the same stratigraphic level. Shallow-water evaporites in areas such as Sicily, which show two cycles separated by an unconformity (Butler et al., 1995), may be of somewhat different age from the deep basin evaporites. The detailed stratigraphic relations of the basinal and shallow-water evaporites remains a topic of debate (cf. Benson and Rakic-El Bied, 1991; Butler et al., 1995; Clauzon et al., 1996). Most work on Messinian evaporites has been carried out in the western Mediterranean. Zhang (1996 and pers. commun.) has suggested that distribution of *Globorotalia conomiozea* and of Indian Ocean echinoids in the Mediterranean indicates complete separation at times of the eastern and western Mediterranean basins in the Miocene, with the eastern Mediterranean linked to the Indian Ocean.

Previous work on shallow-water Messinian evaporites in the western Mediterranean has shown that they interbed with principally carbonate sedi-

* Corresponding author.

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ments (Rouchy and Saint Martin, 1992; Pedley and Grasso, 1994). In this paper, we describe evaporite sequences in the island of Zakynthos off western Greece, that interbed with terrigenous turbidites. We are unable to contribute new stratigraphic controls, but our interpretation of the sedimentology of these deposits will contribute to the understanding of the depositional environment of Messinian evaporites in the eastern part of the Mediterranean and study of palynomorphs provides new information on palaeoenvironmental conditions at the time.

1.1. Previous work

Messinian gypsum in Zakynthos outcrops in several localities along the south coast of the island (Fig. 1). The gypsum is 20–100 m thick. Previous workers have interpreted the gypsum as being of littoral to sabkha origin (Braune and Heimann, 1973; Heimann, 1977; Fabricius et al., 1978), and ascribed the variation in thickness to rapid subsidence (Heimann et al., 1975). These authors point out an association of gypsum in the Ionian islands with reef-like structures with shallow water algae and Messinian foraminiferal assemblages that indicate water depths of 60–180 m (Braune et al., 1978). In this paper, we distinguish two facies types of Messinian gypsum and under- and overlying sediments. Principally shallow water sediments are found in southeastern Zakynthos, whereas deeper water Miocene facies are developed on the south coast of central Zakynthos.

2. The gypsum unit of central Zakynthos

2.1. Agios Sostis-stratigraphy

We have examined in detail the section at Agios Sostis (Figs. 1, 2). Five units are distinguished.

(1) The basal 55 m consists of mudstones with interbedded thin turbidite sandstones, with a sandstone:shale ratio of 1:2. The sandstones form Bouma sequences, principally T_{ab}, T_{bc} and T_{ae}. Their resedimented character is confirmed by their microfossils (Dermitzakis, 1977). Equivalent strata in the Laganas section are from foraminiferal zone

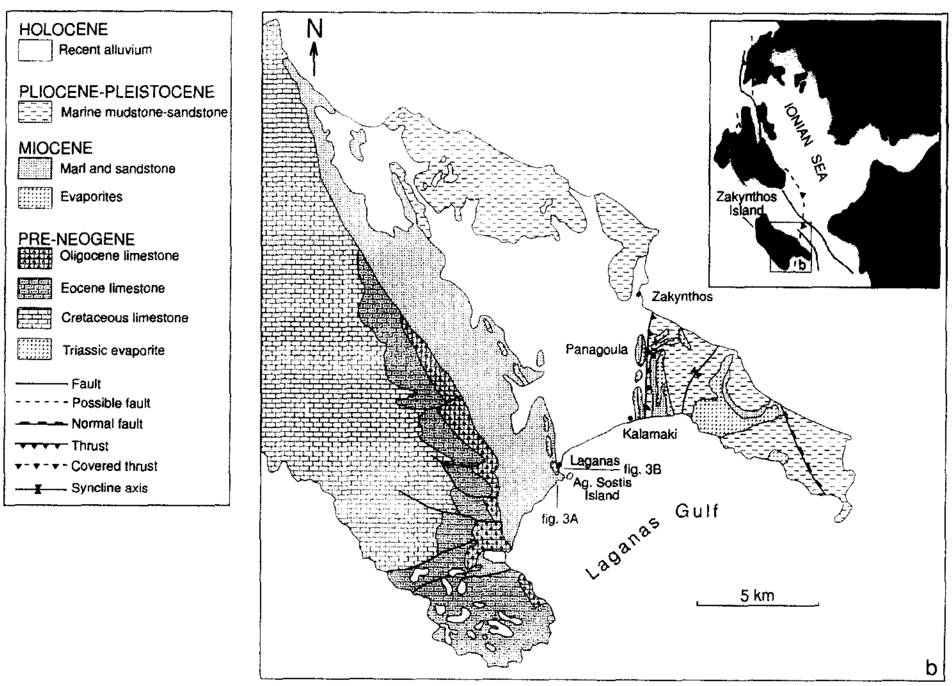

Fig. 1. Geological map of southern Zakynthos showing location of the studied sections.

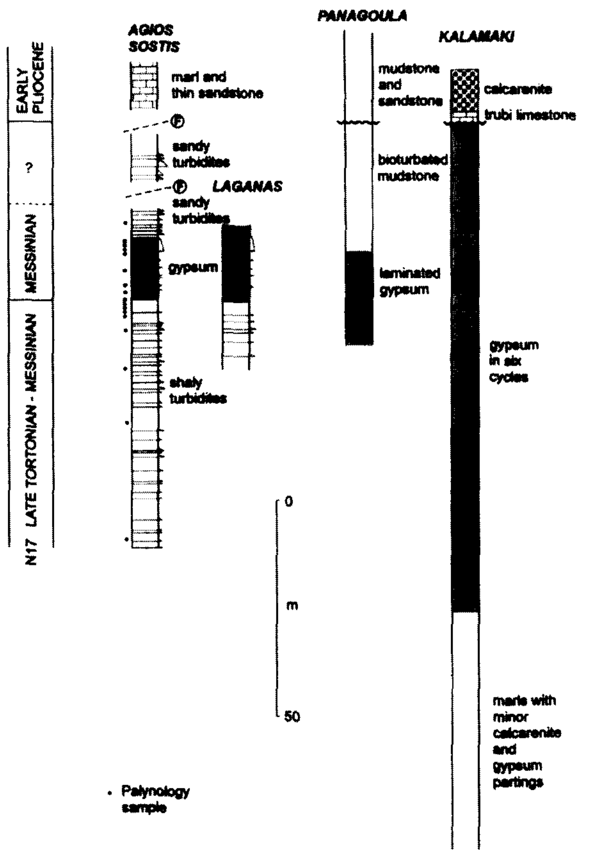

Fig. 2. Summary stratigraphic sections of the gypsum unit on Zakynthos.

N17 (late Tortonian to Messinian) (Bizon and Bizon, 1985).

(2) A 14 m thick section of gypsum, which is described in detail below. The basal part of the gypsum has some interbedded sandstone and the entire gypsum unit appears conformable on the underlying turbidite succession. Four cycles are recognised within the gypsum unit, each topped by a <15 cm marly bed.

(3) Conformably overlying the gypsum unit are 8 m of grey shales with interbedded gypsum beds and terrigenous turbidite sandstones.

(4) Agios Sostis island, separated by a fault from the main coastal section, exposes a 12 m thick fining-up succession of sandy turbidites, generally with a 9:1 sandstone to shale ratio. The lowest beds are up to 1 m thick T_{ab} beds with mudstone intraclasts, but most sandstones are T_{bc} beds 5–20 cm thick. Palaeocurrents determined from groove casts and cross-lamination are towards NE. Some slumped horizons involving both sandstone and mudstone are also present.

(5) Again with fault separation, a coastal section exposes 12 m of marls with about 10% fine–medium grained sandstones 4–20 cm thick. Sedimentary structures in the sandstones including hummocky cross-stratification suggest that they are storm deposits. These marls correspond to the "trubi" limestone typical of the lower Pliocene of the Mediterranean.

The terrigenous sediments overlying the gypsum contain a non-diagnostic nannofossil flora including reworked Eocene taxa; the Pliocene marls have an NN12/NN13 nannofossil assemblage (Frydas, 1986).

No direct field evidence is seen for significant erosional unconformities within the gypsum section. The possibility of an erosional surface in the apparently faulted interval beneath the uppermost sandy turbidite cannot be excluded.

2.2. *Sedimentology of the gypsum unit at Agios Sostis*

Two principal facies are present in the gypsum unit. Some beds are unequivocally resedimented gypsum, in beds 20–130 cm thick, with sharp bases, and Bouma turbidite sequences T_{ab} and T_{abc} (Fig. 3a). The thickest bed is a 2.5 m thick gypsum conglomerate with clasts up to 1 cm in size, the top of which grades up into sand-grade gypsum (Fig. 3b). Other beds have gypsum of coarse sand grade at their base. At the base of the gypsum unit, several T_{abc} beds of gypsum are interbedded with grey shales and with T_b terrigenous sandstone beds. At the top of the gypsum unit grey shales contain interbedded graded beds with Bouma sequences both of gypsum and of terrigenous sand. All these gypsum beds are interpreted as turbidites, on the basis of sedimentary structures and the fact that they interbed with typical terrigenous turbidites.

The other facies in the gypsum unit consists of well laminated gypsum, locally with marly intercalations up to 15 cm thick. In places, this laminated gypsum has sharp based beds and wavy lamination

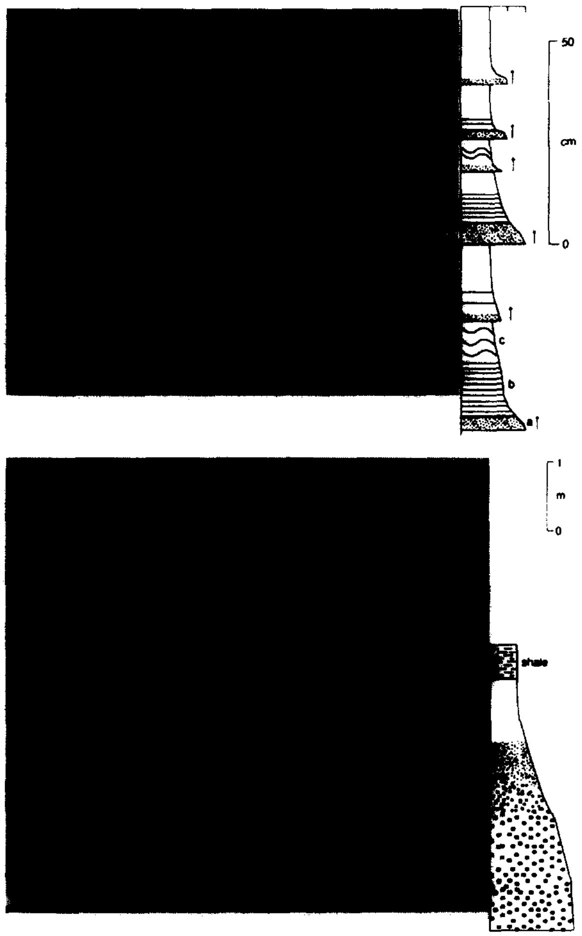

Fig. 3. Interpreted photographs of selected sedimentary structures in the gypsum unit of Agios Sostis. (A) Interpretation of laminated gypsum section as a series of gypsum turbidites. ↑ indicates inferred base of beds, *e*=erosive base; *a*, *b*, *c* are inferred Bouma divisions. (B) 3.5 m thick conglomeratic gypsum bed at Laganas.

at the top of 2–10 cm beds. The bases of some beds erode underlying structures and some beds show flame structures. Much of this laminated sequence appears to be T_{ab}, T_{abc*} and T_{bc*} turbidites (where the c* division is wavy laminated, locally with asymmetric ripple cross-lamination), in which the b division predominated. However, the possibility that some of the laminated gypsum was precipitated in situ cannot be excluded on sedimentological grounds.

Four sulphur isotope determinations were made (Table 1) on gypsum samples. These suggest an

Table 1
Sulphur isotope determinations

Height above base of gypsum unit (m)	$\delta^{34}S$ (‰)	
2	+24.8	
9	+24.3	
13	+22.9	Coarse crystals at base of thick bed
14	+23.0	Middle of thick bed

Determinations by Krueger Enterprises, Inc., Geochron Laboratories Division.
$^{34}S/^{32}S$ standard is Canon Diablo troilite=0.0450045.

upward decrease in $\delta^{34}S$ from 24.8‰ near the base of the section to 22.9‰ in the coarse bed near the top of the section. These values are consistent with late Miocene evaporites elsewhere (Claypool et al., 1980). It is not clear whether the upward decrease in $\delta^{34}S$ is significant, reflecting decreased removal of light sulphide by bacterial reduction once evaporitic conditions set in.

2.3. *Palynology of the Agios Sostis section*

Of the eight samples from the shaly turbidites underlying the gypsum (Fig. 2), most had abundant wood and leaf particles, common poorly preserved (oxidised) pollen and variable amounts of well preserved dinoflagellates. High ratios of pollen to dinocysts reflect redeposition of sediments with a high terrigenous content (e.g., McCarthy and Mudie, 1996). Absence of compression and thermal alteration suggests that if there is reworking of terrigenous organics, it is largely penecontemporaneous. Samples from 7 m and 23 m below the base of the gypsum contained only finely dispersed kerogen, fragments of pine pollen and rare dinocysts of probable Early–Middle Miocene age. The well-preserved dinocyst assemblages show no evidence of reworking. From 3 m to 52 m below the base of the gypsum, pollen is dominated by *Pinus* and *Picea*, with common *Carya* and *Platycarya* and rare *Liquidambar*, suggesting a warm moist climate. The absence of *Taxodium* pollen indicates that significant Late Miocene climatic cooling had already taken place (cf. Bertolani-Marchetti, 1985). Well-preserved dinoflagellate assemblages in most of this section contain a low diversity (2–5 species) of neritic species, with *Achomosphaera andalousiense*, *Lingulodinium machaerophorum* and *Tectatodinium psilatum* possibly indicating relatively low salinity (the latter two species are common in Quaternary sediments of the Black Sea: Wall et al., 1973). The dinocyst assemblage at −3 m, however, is relatively diverse (11 spp.) and quite similar to the neritic marine Tortonian flora at the Castellanian stratotype (Powell, 1986).

The top of the shaly turbidite section (2–0 m) has common *Pinus*, *Picea* and *Tsuga*, minor alder, Chenopodiaceae and Compositae and rare *Carya*, suggesting a colder climate and montane vegetation source. Dinoflagellates in these samples are of Messinian age, with *Galeacysta etrusca*, *L. machaerophorum*, *Spiniferites*, *Achomosphaera* and *Impagidinium* spp. dominant, quite similar to low salinity assemblages in the Italian Cava Serradi section (Corradini and Biffi, 1988) and to upper bathyal assemblages at the top of the Castellanian superstage stratotype (Powell, 1986).

Of three gypsum samples examined, one is barren and one contains only a few *Pinus*. A sample from near the base of the gypsum unit contains *Pinus* and dominant Chenopodiaceae, common Graminae and Compositae, suggesting cool, dry conditions on land. The dinocyst diversity is low (7 spp.), but the presence of *Impagidinium* spp. indicates an open marine environment of normal salinity (Wall et al., 1977). These data support the sedimentological evidence that the gypsum is resedimented.

The shales immediately overlying the gypsum unit have a late Miocene to early Pliocene dinoflagellate assemblage dominated by *L. machaerophorum*, *Achomosphaera* and *Spiniferites* spp., with occasional *Hystrichokolpoma* and rare *Sumatradinium* spp. suggesting an outer neritic marine environment. The pollen is a temperate assemblage including *Juglans*, *Carya*, *Quercus*, some *Alnus* and relatively abundant ferns, implying conditions wetter than present. Wood fragments are very common.

2.4. *The gypsum unit at Laganas*

The Laganas section is about 200 m east of Agios Sostis. It shows similar sedimentological features to the Agios Sostis section, with the same four cycles each capped by marl. However, the section is coarser than at Agios Sostis, with several sand sized beds >50 cm thick. The conglomerate unit consists of 2.5 m of conglomerate (mean clast size 7 cm, maximum 30 cm) capped by a 1.5 m thick sand-sized gypsum bed (Fig. 2). This suggests that the section is laterally equivalent to Agios Sostis, but closer to the axis of a submarine valley.

3. The gypsum unit of Eastern Zakynthos

The Kalamaki section is about 4 km east of Agios Sostis (Fig. 1). At the base, 55 m of marls with minor calcarenites and gypsiferous partings are overlain by the main gypsum unit which is 113 m thick (Fig. 2). This unit comprises six cycles 9–14 m thick, each capped by marl. The upper three cycles consist of nodular gypsum and gypsum conglomerates interbedded with laminated and crystalline gypsum. An erosional unconformity separates the gypsum unit from the Pliocene trubi limestone (2 m) and overlying calcarenites (10 m).

At Panagoula, 3 km north of Kalamaki, the gypsum unit consists of 20 m of banded gypsum overlain by 29 m of bioturbated olive-grey mudstone. This is unconformably overlain by Pliocene mudstones with *Cardium* and sandstones. *Cladocera coespitosa* is found in growth position on the unconformity surface.

The gypsum unit in the east of Zakynthos appears to be a shallow water deposit, with nodular and banded gypsum, but no clear turbidite deposits. In contrast to Agios Sostis, where the gypsum unit is overlain by terrigenous turbidites, in eastern Zakynthos the unit is unconformably overlain by shallow-water Pliocene sediments.

4. Discussion

The sedimentological data from the Agios Sostis and Laganas sections of central Zakynthos show that the Messinian gypsum unit consists of turbidites and is both over- and underlain by terrigenous turbidite successions. The lack of unconformities in the terrigenous to gypsum turbidite succession and the presence of marine dinoflagellates in at least the lower part of the gypsum unit indicate that the gypsum turbidites accumulated under marine conditions. If there was complete desiccation of the basin and the development of a regional unconformity, it can occur only in the faulted interval of >20 m of terrigenous turbidites (maximum thickness unlikely more than 50 m) overlying the gypsum. These terrigenous turbidites are succeeded by sandstones with hummocky cross-stratification indicating deposition in shelf depths influenced by storm waves. If the area experienced no significant tectonic uplift, this would suggest that the gypsum unit turbidites accumulated in water depths of 50–150 m.

In contrast, we agree with the interpretation of Braune and Heimann (1973) that the gypsum in the eastern part of the island is of shallow water origin and is not resedimented. It is unconformably overlain by shallow water Pliocene sediments, suggesting sea level fall during the Messinian. This sea level fall may have created conditions for resedimentation of shallow-water gypsum to deposit the thick gypsum conglomerate in the central part of the island. It is possible that there is an erosional surface in the faulted interval beneath the uppermost sandy turbidite succession at Agios Sostis, corresponding to the unexposed interval above the Laganas gypsum and the unconformity at Panagoula and Kalamaki (Fig. 2). Elsewhere in the eastern Mediterranean, the largest sea-level fall probably occurred in the late Messinian (Druckman et al., 1995; cf. Clauzon et al., 1996). The pollen suggests a transition from warm temperate conditions before the gypsum unit, to arid conditions during deposition of the gypsum unit, to moist temperate conditions in the earliest Pliocene.

Messinian gypsum was precipitated under evaporitic conditions in shallow water in southeastern Zakynthos. Some of this gypsum was resedimented to form the gypsum turbidite succession of central Zakynthos, that accumulated in water depths of less than a few hundred metres of water and is interbedded with terrigenous turbidites. At least in the lower part of the gypsum unit in central Zakynthos, the ambient seawater was not significantly hypersaline. Similar basin-margin conditions have been inferred for the Messinian of Sicily (Vai and Ricci Lucchi, 1977; Pedley and Grasso, 1994; Butler et al., 1995). As elsewhere in the Hellenide orogen (Kontopoulos et al., 1996), Messinian sedimentation took place under conditions of tectonic activity that led to turbidite sedimentation and rapid facies changes.

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